# Towards More Coherent Sources Using a Microstructured Chalcogenide Brillouin Fiber Laser

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***Abstract*—Up to 16 dB frequency noise reduction and a linewidth 8 times narrower that of the pump source is reported for the Stokes component in a compact Brillouin fiber laser made of chalcogenide microstructured fiber. Since the pump wave is not resonant in the ring cavity, an active stabilization of the laser is not primordial thus making the system simpler and cheaper. Although only a 3 metre-long microstructured chalcogenide fiber was used as gain medium, a very low laser threshold power of 6 mW was obtained for nonresonant pumping. The linewidth-narrowing effect achieved in our BFL cavity is also discussed.**

***Index Terms*—Chalcogenide optical fiber, microstructured optical fibers, Brillouin fiber lasers, frequency noise, linewidth.**

## I. Introduction

THE demand for coherent laser sources with low intensity noise and frequency noise has been increasing recently because they are crucial for many applications such as in optical communication systems and microwave photonics [1]. One way to reduce the frequency noise of a laser is to exploit stimulated Brillouin scattering in an all-fiber ring-resonator in order to obtain a Brillouin fiber laser (BFL). The Stokes line thus generated demonstrates not only an intensity noise reduction [2] but most importantly a very narrow linewidth, potentially several orders of magnitude narrower than that of the pump source [3]. In fact, the BFL acts as an efficient low-pass filter since the transfer of the pump fluctuations to the Stokes line is mainly governed by the acoustic phonon lifetime. The frequency noise of a laser being intimately linked to its linewidth, it goes without saying that the frequency noise of the laser is reduced as well.

Silica fibers are usually used to make BFLs. However, due to the relatively small Brillouin gain coefficient $g_B$ in silica and their narrow Brillouin bandwidth, BFLs are generally constructed in an all-fiber, high-finesse ring-resonator arrangement with resonant pumping to achieve submilliwatt laser thresholds [4]. For stable and efficient lasing, the pump signal must coincide with one of the resonator modes in the ring cavity. This can be achieved by actively locking either the ring resonator to the pump frequency by using a fiber stretcher [4] or the pump frequency to the ring cavity. In 2006, *Geng et al.* obtained more than 10 dB frequency noise reduction of the Stokes line as compared to its pump source [5]. However, such results required the use of complex and expensive electronic devices in order to set up a Pound-Drever-Hall technique. The requirement for a critically coupled resonator can be solved in a BFL by using an optical circulator to inject the pump inside the cavity to allow free propagation for only the Stokes waves. The pump waves are thus non-resonant in the cavity and the latter no longer requires to be servo-locked. This results in an increase in the laser threshold for the BFL leading to the use of longer fibers to achieve Brillouin threshold at a reasonable pump power. A similar BFL was made using a 110-metre long silica fiber [6]. The BFL was however unstable due to the simultaneous existence of several longitudinal modes. This problem can be easily overcome by using fibers with higher $g_B$. For instance, single-frequency lasing was achieved in a 49-cm-long bismuth-based erbium-doped fiber [7] with 144 mW pump power. This laser threshold can be reduced by using chalcogenide fibers reported to have a $g_B$ two orders of magnitude higher than in standard silica fibers [8-11]. In another communication, we demonstrated a low laser threshold of 22 mW and experimentally showed both intensity and frequency noise reduction for a compact Brillouin laser made of 3 meters microstuctured chalcogenide fiber.

The purpose of this letter is : first of all to report an even lower laser threshold obtained by using a microstructured fiber made of a different composition of chalcogenide glass with very low transmission losses of 0.65 dB/m and, secondly, to study in a more exhaustive way the frequency noise reduction achieved in such cavities. In the first part, the fiber used in this communication will be presented. Then, the Brillouin fiber laser will be detailed and finally frequency reduction and linewidth-narrowing will be experimentally measured and the results discussed in the last part.

## II. $Ge_{10}As_{22}Se_{68}$ Brillouin fiber laser

The single-frequency BFL used in this letter is fully described in [12]. Since our goal is to reduce the laser threshold in our BFL, we have replaced the suspended-core $As_{38}Se_{62}$ gain medium previously used with another chalcogenide fiber, namely a monomodal $Ge_{10}As_{22}Se_{68}$ microstructured optical fiber (MOF) (inset of Fig. 1), with a lower transmission losses $\alpha$ of 0.65 dB/m at 1.55 $\mu$m. This fiber, prepared by a casting method [13], had an external diameter of 140 $\mu$m, a core diameter of 3.8 $\mu$m and a mode effective area estimated to be around 8 $\mu m^2$.

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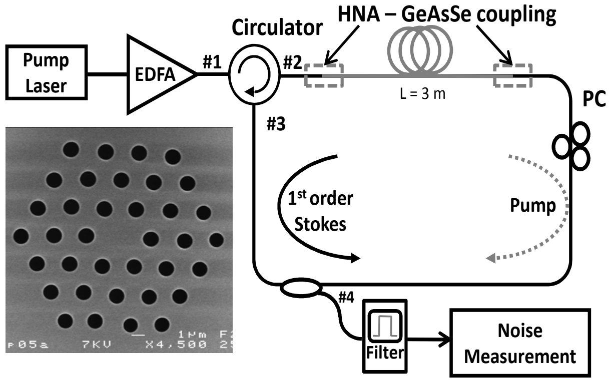


Fig. 1. Configuration of the BFL ring cavity. Inset is the transverse section of the GeAsSe MOF used. Abbreviations are as follows: EDFA (Erbium Doped Fiber Amplifier); HNA (High Numerical Aperture); PC (Polarisation Controller).

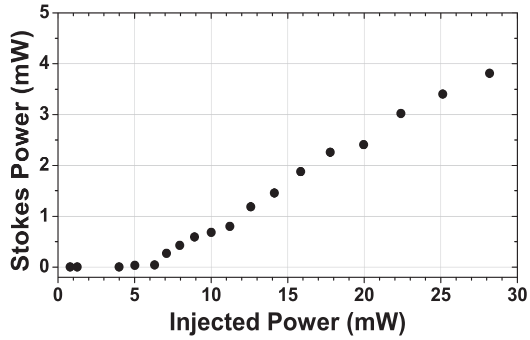


Fig. 2. BFL output power as a function of injected pump power.

A complete experimental characterization of Brillouin scattering in our GeAsSe MOF was performed. A $g_B$ of $4.4 \times 10^{-9}$ m/W was determined using the setup and method detailed in [10] as well as a Brillouin frequency shift $\nu_B$ of 7.25 GHz and a Brillouin gain linewidth $\Delta\nu_B$ of 17 MHz. These values are slightly different to those measured and predicted in [11]. This can be explained by the presence of germanium in the fiber composition [14].

As shown in Fig. 1, the laser cavity is composed of 3 m of GeAsSe fiber and 5 m of SMF-28 fiber resulting in a total optical cavity length of 15.08 m ($5 \times 1.45 + 3 \times 2.61$) This corresponds to a free spectral range (FSR) of 19.9 MHz, which is more than the measured Brillouin gain bandwidth $\Delta\nu_B$ of 17.6 MHz, ensuring that only one single longitudinal mode is oscillating inside the cavity. The cavity was placed in a specific container to control the temperature shift and isolated from mechanical vibrations by placing air cushions on the experimental table in order to prevent variations of the cavity length. The pump source used consists of an Erbium-doped fiber amplifier (EDFA) feeded by a commercial fiber laser module, Koheras Basik. The output of the BFL is extracted from a 10 % fiber coupler while the remaining 90 % is fed back into the cavity. An optical circulator is used to close the ring cavity, thus allowing free propagation of the Stokes waves, which perform multiple roundtrips, while the pump wave interacts only over a single loop. The main advantage of this cavity over a conventional ring resonator cavity is that there are no resonant conditions for the pump, and thus, no need to servo-lock it with a feedback loop. A high numerical aperture (HNA) fiber, with a mode field diameter and a numerical aperture measured to be respectively 3.16 $\mu m$ and 0.35, is used to optimise the coupling of light inside the chalcogenide fiber. A polarization controller is inserted inside the cavity to ensure that the polarization of the pump is kept parallel to that of the Stokes wave to yield maximum Brillouin gain since our fiber is not polarization-maintained. The total round-trip linear losses, which includes 1.95 dB due to transmission losses in the chalcogenide fiber, 1 dB due to Fresnel reflection, 2.5 dB of coupling losses and 2.5 dB across the optical components in the ring cavity, is estimated to be around 7.95 dB.

Figure 2 illustrates the BFL output Stokes power as a function of the injected pump power in the chalcogenide fiber. Since the pump power is launched in the clockwise (CW) direction with respect to Fig. 1, the Stokes wave propagates in the counterclockwise (CCW) direction and is coupled out of the ring cavity at port #4 of the coupler. When the injected power is above 6 mW, the measured power is approximately proportional to the pump power, indicating Brillouin lasing on the first Brillouin shift with around 18 % slope efficiency and a very low threshold of about 6 mW for single pass pumping, which is lower than the 22 mW laser threshold obtained in a previous work in a suspended-core $As_{38}Se_{62}$ (AsSe) chalcogenide fiber [12]. This can be explained by the reduced transmission and coupling losses achieved in our GeAsSe fiber as well as its monomodal nature.

## III. Frequency noise reduction and linewidth narrowing of the Stokes component

Due to the high refractive index of the GeAsSe glass ≈ 2.61 at a wavelength of 1.55 $\mu$m), part of the injected signal is back-reflected at the entry facet of the fiber and extracted as well from port #4 of the output coupler as shown in Fig. 3. Hence, a commercial tunable filter from Yenista (frequency bandwidth of 6 GHz) was added in the setup to get rid of any residual pump contribution in our noise measurements.

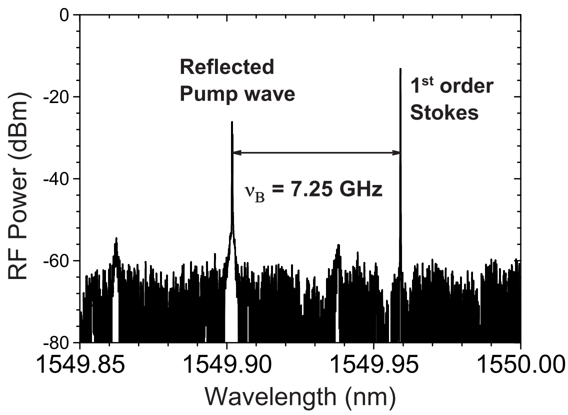


Fig. 3. Optical spectrum extracted from port #4 of the coupler.

Beforehand one would expect the low-pass filtering function to bring a frequency noise reduction in the Stokes component.

The frequency noise of the Stokes component of the BFL was measured using a correlated delayed self-heterodyne method [15] with a fiber length delay of 15 m. This method is based on the traditional delayed self-heterodyne technique commonly used to measure the spectral linewidth of laser sources with the exception that the signal on both arms remains correlated. In this configuration, the output is proportional to the frequency fluctuations of the laser and the use of a phase noise measurement bench gives us access to the frequency noise of our laser; the phase fluctuations of the RF beat signal being proportional to the frequency fluctuations of the laser.

The measured frequency noise of the BFL was plotted on Fig. 4. The frequency noise of the pump source (pump laser + EDFA) was included as well as on the same plot. It is worth noting that 16 dB frequency noise reduction is observed for the Stokes component as compared to the pump source at an arbitrarily chosen frequency of 20 kHz. The frequency noise reduction obtained in the low frequency region, that is below 1 kHz, is not very precise since excess noise, possibly brought by the EDFA and acoustic pick-up noise, adds up to our measured frequency noise.

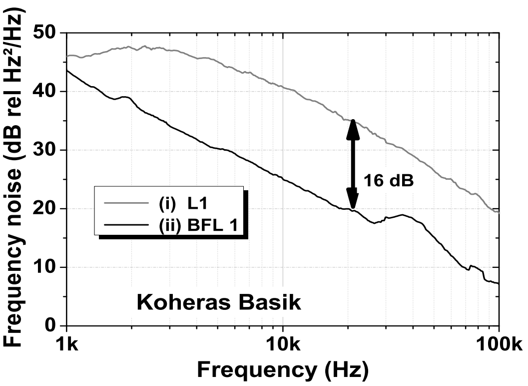


Fig. 4. BFL output power as a function of injected pump power.

Moreover, indications about the linewidth of the laser can be obtained by exploiting the frequency noise spectrum. Although it is very common to determine the coherency of a laser by measuring its spectral linewidth using a self-heterodyne technique [16], this parameter is difficult to measure for spectrally very pure sources since their coherent length exceeds hundreds of kilometers. An alternative is to use the frequency noise spectrum to evaluate the spectral linewidth of a laser. Indeed, a frequency noise spectrum is usually made up of two parts: a white noise component which gives a Lorentzian lineshape $\Delta\nu_L$ and flicker noise in the lower frequency range corresponding to a Gaussian lineshape $\Delta\nu_{3dB}$. As we can see on Fig. 4, flicker noise is the dominant noise contribution since we are dealing with fiber lasers. $\Delta\nu_{3dB}$ can thus be estimated by integrating the frequency noise spectra, which is directly linked to $\Delta\nu_{3dB}$ via the equation $\Delta\nu_{3dB}$ = 2.35 $\sqrt{\int_{1k}^{100k} S_{\Delta\nu}(f)df}$ [17], where $S_{\Delta\nu}(f)$ is the frequency noise power density measured in $Hz^2/Hz$. This gives a $\Delta\nu_p$ of respectively around 47 kHz and a $\Delta\nu_s$ of 5.3 kHz for the pump source and the Stokes component. In order to validate our results, the expected linewidth of the Brillouin laser obtained from a particular pump laser can be predicted by using the equation given in reference [3]:

$$\Delta\nu_{th} = \frac{\Delta\nu_p}{(1+\gamma_A/\Gamma_c)^2} \tag{1}$$

where $\gamma_A$ is the damping rate of the acoustic wave, defined by $\pi\Delta\nu_B$. $\Gamma_c$ is the cavity loss rate. By taking into consideration all the losses and the reinjection rate of our cavity, a value of around 8 is calculated for $(1+\gamma_A/\Gamma_c)^2$. This value can be increased by decreasing the overall losses in our cavity and by using a coupler with a higher coupling rate. Replacing $\Delta\nu_p$ by 47 kHz, a linewidth of 5.9 kHz is obtained, which is not too far from the measured value of 5.3 kHz.

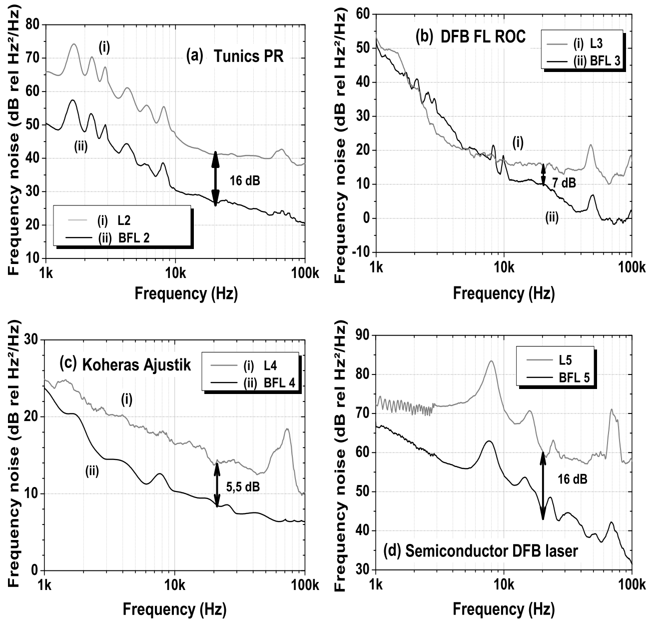


Fig. 5. Frequency noise spectra of (i) pump source (ii) Stokes component for different pump laser sources; namely (a) external cavity Tunics-PR, (b) distributed feedback fiber laser ROC (c) Koheras Ajustik and (d) distributed feedback semiconductor laser.

The same experiment was repeated using four other lasers: (i) a commercial tunable laser, Tunics PR (L2), (ii) a bare distributed feedback fiber laser pumped at 1480 nm (L3), (iii) a thermally and acoustically isolated fiber laser, Koheras adjustik (L4) and (iv) a distributed feedback semiconductor laser commonly used in telecommunication (L5). As earlier, the frequency noise reduction between the Stokes component and the pump source of the four lasers (Fig. 5) were measured and the Gaussian and Lorentzian distribution to linewidth of the Stokes components estimated. These results are tabulated in table I. It is interesting to note that for laser sources with $\Delta\nu_p$ higher or equal to 47 kHz (L1, L2 and L5), the same frequency noise reduction is obtained (16 dB) as well as an agreement between the measured and the expected linewidth of the Stokes component. For more coherent sources (L3 and L4), a $\Delta\nu_S$ of around 1.8 kHz is measured for both the Stokes components of L3 (BFL3) and L4 (BFL4) and a lower frequency noise reduction also noted although one would have expected the same 16 dB frequency noise reduction

| Laser | Frequency noise reduction (dB) | $\Delta\nu_p$ (kHz) | $\Delta\nu_s$ (kHz) | $\Delta\nu_{th}$ (kHz) |
|---|---|---|---|---|
| Koheras Basik (L1) | 16 | 47 | 5.3 | 5.9 |
| Tunics PR (L2) | 16 | 367 | 45.4 | 45.9 |
| DFB FL ROC (L3) | 7 | 5.8 | 1.88 | 0.73 |
| Koheras Ajustik (L4) | 5.5 | 4.1 | 1.81 | 0.51 |
| DFB semicon. laser (L5) | 16 | 1950 | 266 | 244 |

TABLE I
COMPARISON OF THE FREQUENCY NOISE REDUCTION IN BFLS. $\Delta\nu_p$ : PUMP SOURCE LINEWIDTH; $\Delta\nu_s$ : BFL MEASURED LINEWIDTH; $\Delta\nu_{th}$ : BFL ESTIMATED LINEWIDTH.

as well as a spectral linewidths of 730 Hz and 510 Hz for respectively BFL3 and BFL4 according to equation (1). This can be explained by the fact that the linewidths of BFL3 and BFL4 are so narrow that it is the environmental noise due to acoustic vibrations and temperature variations rather than the real linewidth that is being measured by our bench; resulting in an excess frequency noise contribution and larger linewidth of our BFL. This means that our laser cavity was not properly packaged because although the precautions mentioned above were taken, it was still sensitive to external perturbations.

## IV. CONCLUSION

In conclusion, a simple method based on a Brillouin fiber laser to reduce the frequency noise, and thus increase the coherency of a laser, is demonstrated. The Brillouin fiber laser used does not require active control of the cavity and has a very low threshold of 6 mW despite the fact that it is pumped in a non-resonant way since we used a low-loss, monomode microstructured chalcogenide fiber as Brillouin gain medium. The BFL acts as a low-pass filter : up to 16 dB frequency noise reduction of the Stokes component as well as a linewidth 8 times narrower than that of the pump source was obtained with our cavity. This linewidth narrowing effect can further be increased by reducing the overall losses in our cavity and by using a coupler with a higher coupling rate.

## ACKNOWLEDGMENT

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## REFERENCES

[1] S. Norcia, S. Tonda-Goldstein, D. Dolfi, J.-P. Huignard, and R. Frey, “Efficient single-mode brillouin fiber laser for low-noise optical carrier reduction of microwave signals,” *Opt. Lett.*, vol. 28, no. 20, pp. 1888–1890, Oct 2003.

[2] L. Stepien, S. Randoux, and J. Zemmouri, “Intensity noise in brillouin fiber ring lasers,” *JOSA B*, vol. 19, no. 5, pp. 1055–1066, May 2002.

[3] A. Debut, S. Randoux, and J. Zemmouri, “Linewidth narrowing in brillouin lasers: Theoretical analysis,” *Phys. Rev. A*, vol. 62, p. 023803, Jul 2000.

[4] S. Molin, G. Baili, M. Alouini, D. Dolfi, and J.-P. Huignard, “Experimental investigation of relative intensity noise in brillouin fiber ring lasers for microwave photonics applications,” *Opt. Lett.*, vol. 33, no. 15, pp. 1681–1683, Aug 2008.

[5] J. Geng, S. Staines, Z. Wang, J. Zong, M. Blake, and S. Jiang, “Highly stable low-noise brillouin fiber laser with ultranarrow spectral linewidth,” *Photonics Technological Letters, IEEE*, vol. 18, no. 17, pp. 1813–1815, Sep 2006.

[6] F. Mihélic, D. Bacquet, J. Zemmouri, and P. Szriftgiser, “Ultrahigh resolution spectral analysis based on a brillouin fiber laser,” *Optics letters*, vol. 35, no. 3, pp. 432–434, 2010.

[7] S. Harun, R. Parvizi, S. Shahi, and H. Ahmad, “Compact bi-edf-based brillouin erbium fiber laser operating at the 1560-nm region,” *Photonics Journal, IEEE*, vol. 1, no. 5, pp. 254–258, 2009.

[8] K. Abedin, “Observation of strong stimulated Brillouin scattering in single-mode As2Se3 chalcogenide fiber,” *Optics Express*, vol. 13, no. 25, pp. 10 266–10 271, 2005.

[9] C. Florea, M. Bashkansky, Z. Dutton, J. Sanghera, P. Pureza, and I. Aggarwal, “Stimulated Brillouin scattering in single-mode As2S3 and As2Se3 chalcogenide fibers,” *Optics Express*, vol. 14, no. 25, pp. 12 063–12 070, 2006.

[10] J. Fatome, C. Fortier, T. Nguyen, T. Chartier, F. Smektala, K. Messaad, B. Kibler, S. Pitois, G. Gadret, C. Finot *et al.*, “Linear and nonlinear characterizations of chalcogenide photonic crystal fibers,” *Journal of Lightwave Technology*, vol. 27, no. 11, pp. 1707–1715, 2009.

[11] R. Cherif, M. Zghal, and L. Tartara, “Characterization of stimulated brillouin scattering in small core microstructured chalcogenide fiber,” *Optics Communications*, vol. 285, no. 3, pp. 341 – 346, 2012.

[12] K. H. Tow, Y. Léguillon, P. Besnard, L. Brilland, J. Troles, P. Toupin, D. Méchin, D. Trégoat, and S. Molin, “Relative intensity noise and frequency noise of a compact brillouin laser made of as38se62 suspended-core chalcogenide fiber,” *Opt. Lett.*, vol. 37, no. 7, pp. 1157–1159, Apr 2012.

[13] P. Toupin, L. Brilland, J. Trolès, and J. Adam, “Small core ge-as-se microstructured optical fiber with single-mode propagation and low optical losses,” *Optical Materials Express*, vol. 2, no. 10, pp. 1359–1366, 2012.

[14] A. Yeniay, J. Delavaux, and J. Toulouse, “Spontaneous and stimulated brillouin scattering gain spectra in optical fibers,” *Journal of lightwave technology*, vol. 20, no. 8, p. 1425, 2002.

[15] S. Camatel and V. Ferrero, “Narrow linewidth cw laser phase noise characterization methods for coherent transmission system applications,” *Journal of Lightwave Technology*, vol. 26, no. 17, pp. 3048–3055, 2008.

[16] L. Richter, H. Mandelberg, M. Kruger, and P. McGrath, “Linewidth determination from self-heterodyne measurements with subcoherence delay times,” *Quantum Electronics, IEEE Journal of*, vol. 22, no. 11, pp. 2070–2074, 2002.

[17] G. Stéphan, T. Tam, S. Blin, P. Besnard, and M. Têtu, “Laser line shape and spectral density of frequency noise,” *Physical Review A*, vol. 71, no. 4, p. 043809, 2005.